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Environmental assessment of mercury contamination from the Rwamagasa artisanal gold mining centre, Geita District, Tanzania

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Abstract

This study presents the results of an environmental assessment of mercury (Hg) contamination in the Rwamagasa artisanal gold mining area, northwest Tanzania, and the potential downstream dispersion along the River Malagarasi to Lake Tanganyika. At the time of sampling, generally low concentrations of Hg (<0.05 mg/kg) occurred in most cultivated soils although higher Hg (0.05–9.2 mg/kg) was recorded in urban soils and vegetable plot soils where these are impacted by Hg-contaminated water and sediment derived from mineral processing activities. Hg in vegetable and grain samples is mostly below the detection limit of 0.004 mg/kg Hg, apart from 0.007 and 0.092 mg/kg Hg in two yam samples and 0.011 to 0.013 mg/kg Hg in three rice samples. The standardized (i.e., standardized to 10 cm length) Hg concentrations in *Clarias* spp. increase from about 0.01 mg Hg/kg for the River Malagarasi delta to 0.07, 0.2, and 1.6 mg/kg, respectively, for the Rwamagasa 'background', moderately and most contaminated sites. For piscivorous (*Lates*, *Brycinus*, and *Hydrocynus* spp.), insectivorous (*Barbus* spp.), and planktivorous (*Haplochromis* spp.) fish species, the 10-cm standardized Hg concentrations increase from about 0.006 mg/kg for the River Malagarasi-Lake Tanganyika area to 0.5 and 3.5 mg/kg, respectively, for the Rwamagasa moderately and most contaminated sites. The low concentrations of Hg in fish from the Malagarasi River delta and Lake Tanganyika indicate that Hg contamination from the Rwamagasa area does not have a readily discernible impact on the biota of Lake Tanganyika. Many of the fish samples from Rwamagasa exceed guidelines for human consumption (0.5 mg/kg) as well as the WHO recommended limit for vulnerable groups (0.2 mg/kg). Tissue total Hg (THg) of all fish collected from the River Malagarasi-Lake Tanganyika subarea is well below these guidelines. Potential human exposure through consumption of 300 g/day of rice grown on Hg-contaminated soils is 5.5 μg/week. Consumption of 250 g Nile perch (*Lates* spp.), 500 g tilapia (*Oreochromis* spp.), and 250 g of catfish (*Clarias* spp.) each week would result in an intake of 65 μg Hg/week for people consuming only fish from the Mara and Mwanza regions of Lake Victoria and 116 μg Hg/week for people in the Rwamagasa area consuming tilapia and Nile perch from Lake Victoria and catfish from mining-impacted streams. This is lower than the Provisional Tolerable Weekly Intake

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(PTWI) of 300 μg for Hg in the diet set by the WHO and the FAO. Inadvertent ingestion of soil containing 9 mg Hg/kg at a rate of 80 mg/day would give an additional estimated weekly intake of 5 μg THg, whereas the persistent and purposeful consumption of soil (geophagia) at a rate of 26 g soil/day would produce an additional chemical exposure of 230 μg Hg/day.
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Keywords: Africa; Sediment; Water; Soil; Fish; Plants; Human exposure; Drainage sediment

1. Introduction

Artisanal gold mining provides income to some of the world's poorest people, many of whom are women and children, but it is also one of the major sources of mercury (Hg) contamination, especially in developing countries. Whereas the gold extraction process (known as amalgamation) is a simple technology, it is potentially very dangerous and contaminates the air, soil, rivers, and lakes with Hg. The health of the miners and other people living within the area affected by Hg contamination may be negatively affected through inhalation of Hg vapour, direct contact with Hg and through eating fish and other food affected by Hg contamination. The Global Environmental Facility (GEF) of the UN funds a project Removal of Barriers to the Introduction of Cleaner Artisanal Gold Mining and Extraction Technologies (also referred to as the Global Mercury Project (GMP; http://www.unites.uqam.ca/gmf/intranet/gmp/front_page.htm) that is currently being executed by UNIDO in six developing countries (Brazil, Indonesia, Laos, Sudan, Tanzania, and Zimbabwe). This paper presents the results of an environmental assessment in the Rwamagasa (or Rwamagaza) artisanal gold mining area, which was selected by UNIDO as the GMP demonstration site for Tanzania. Primary artisanal workings in the Rwamagasa area are centred on quartz veins in sheared, ferruginous, chlorite mica schists. Grab samples of vein and wall rock grade 6–62 g/t Au (Spinifex 2002 Annual Report). One of the objectives of the current study was to assess the impact of Hg contamination on international waters as well as in the immediate vicinity of the Rwamagasa 'mining hotspot'. Consequently, the field programme was carried out in two subareas: (a) the Rwamagasa 'mining hotspot' subarea and (b) the River Malagarasi–Lake Tanganyika subarea (Fig. 1). Dispersion of Hg from Rwamagasa to Lake Tanganyika is probably relatively unlikely because contaminant Hg will be adsorbed by organic material in the extensive Moyowozi and Njingwe Swamps and flooded grassland area, located from 120 to 350 km downstream of Rwamagasa (Fig. 1). Whereas the swamps will act as a potential biomethylation zone, they will also act as an environmental sink for Hg contamination which is likely to inhibit migration of Hg into the lower reaches of the Malagarasi River and Lake Tanganyika, some 430 km downstream from Rwamagasa. The swamp area was inaccessible within the logistical and budgetary constraints of the current project.

The only legal mining in the Rwamagasa area is carried out within the boundaries of the Primary Mining Licence held by Blue Reef Mines (Fig. 2) where approximately 150 people are involved in mining and mineral processing activities. This is the only site in the Rwamagasa area where primary ore is being mined underground. All other mineral processing activity of any significance is concentrated at the northern margin of Rwamagasa, especially on the land sloping down to the Isingile River (Figs. 2 and 3). In this area, there are about 30 groups of historic and active tailings dumps and about 10 localities where small (200 l) ball mills are operating. The number of people actively involved, at one particular time, in ball milling, sluicing, and amalgamation is probably no more than 300.

Amalgam is burned in a small charcoal fire, which releases Hg to the atmosphere. Retorts are not used. Amalgamation mainly takes place adjacent to amalgamation ponds, which are usually formed of concrete, but sometimes have only wood walls even though environmental legislation dictates that the Hg-contaminated mineral concentrates and tailings should be stored in concrete lined structures. The field programme was carried out during the dry season at which time there was little evidence that large quantities of contaminated tailings were being washed into the Isingile River. However, waste water and tailings from amalgamation 'ponds' were

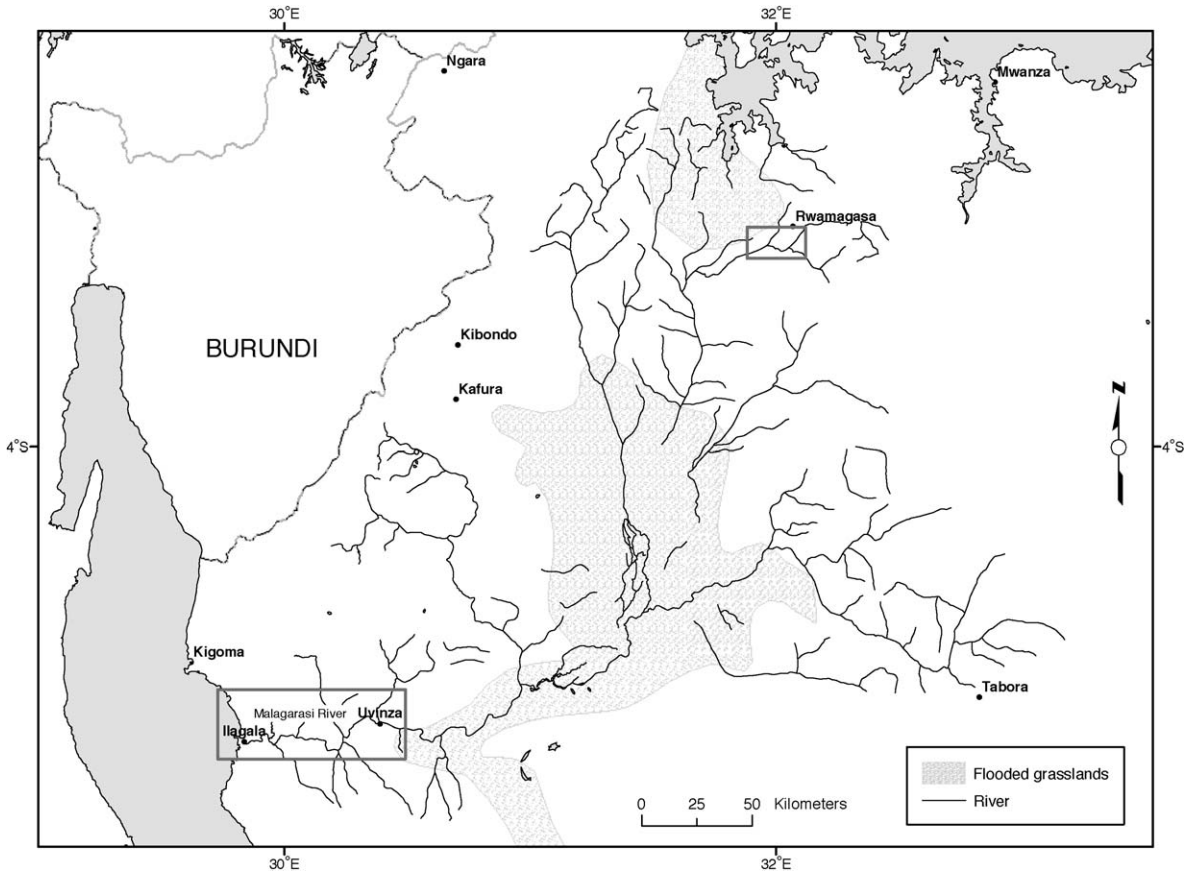


Fig. 1. Location of the River Malagarasi–Lake Tanganyika and Rwamagasa sub-areas in northwest Tanzania.

observed at one site to be overflowing onto an area where vegetables were being grown. If large quantities of Hg-contaminated tailings are dispersed onto the seasonal swamp (*mbuga*) area adjacent to the Isingile River during the wet season, then this may lead to the significant dispersion of Hg both into the aquatic system and onto agricultural sites being used for rice, maize, and vegetable cultivation (Figs. 2 and 3).

Previous studies in the Lake Victoria Goldfields area indicate that dispersion of Hg from tailings is relatively restricted, not least because Fe-rich laterites and seasonal swamps (*mbugas*) act as natural barriers or sinks attenuating the widespread dispersion of Hg in sediments and soils (van Straaten, 2000b). The Blue Reef Mine is reported to produce about 1 kg Au per month whereas artisanal miners re-working tailings produce about 0.5 kg per month (personal communication, John Nayopa, October 2003). On this basis, approximately 27 kg of Hg will be released to the environment from the Rwamagasa area each year. Of this, atmospheric emissions from amalgam burning will be about 14 kg from the Blue Reef mine site and 7 kg from the other amalgamation sites. About 2 to 3 kg Hg will remain in heavy mineral tailings in the amalgamation ponds, which are frequently reprocessed.

The geology and gold mineralization of the region are described by van Straaten (1983), Barth (1990), and Borg (1994). Background information on Hg contamination associated with artisanal gold mining in Tanzania is available in a number of published reports and scientific papers (Gladher et al., 2000; Asano et al., 2000; Campbell et al., 2003a,b; Harada et al., 1999; Ikingura and Akagi, 1996, 2002; Kinabo, 1996, 2002a,b; Kinabo and Lyimo, 2002; Kishe and

Machiwa, 2003; Machiwa et al., 2003; Mutakyahwa, 2002; Semu et al., 1989; Sindayigaya et al., 1994; University of Dar es Salaam, 1994; van Straaten, 2000a,b).

2. Sample collection

2.1. Drainage sediment and water, tailings and soil

Drainage sediment and water were collected from the lower reaches of the Malagarasi River near where it enters Lake Tanganyika (Ilagala) and also from near Uvinza, approximately 60 km upstream (Fig. 1). At Ilagala, sediment samples were collected using a Van Veen grab sampler whilst at Uvinza sediment was obtained from appropriate sites along the bank of the river. Streams in the Rwamagasa area were either completely dry or ponded. Bottom sediment samples, each of 150–200 grams, were collected by wet screening up to 5 kg of river or stream-bed sediment through 2 mm and <150 μm sieves, using a minimal amount of water to avoid the loss of fine silt and clay fractions. Samples were sealed in plastic securitainers to avoid evaporative losses and oxidation. Water samples for Hg analysis were filtered through 0.45-μm cellulose acetate membranes into 30-ml HPDE bottles and preserved with 0.3 ml conc. HNO_3+0.3 ml 0.2 vol.% K_2CrO_7. Thirty millilitre samples of filtered water preserved with 1% v/v HNO_3 were collected for the determination of arsenic. Water samples were stored in a refrigerator before being transported back to the British Geological Survey (BGS) for analysis. A representative selection of channel and composite samples was collected from the historic and recent sluice box tailings and Hg amalgamation 'ponds' (Fig. 3). About 250-g splits of 2–3 kg composite samples were obtained by cone-and-quartering. Composite soil samples (0–15 cm depth) were collected in the Rwamagasa urban area, from adjacent agricultural land and along profiles crossing the seasonal swamp areas (downstream of Rwamagasa). Land use at each soil sample site is indicated in Fig. 2.

2.2. Crops and fish

Mercury in agricultural produce, especially in those forming part of the main diet, was evaluated by collection and analysis of bean, cabbage, maize, onions, rice, tomato and yam samples. The vegetable and rice plots and some of the maize plots located on the *mbuga* area immediately north of Rwamagasa are irrigated using water from the Isingile River (which was ponded at the end of the dry season, and not flowing). Vegetable samples were collected from a site within 5–10 m of an amalgamation pond where water presumed to be Hg-contaminated was overflowing onto cultivated ground (samples 110 and 113, Table 6). Other vegetable samples were obtained from vegetable gardens located on the northern side of the Isingile River *mbuga*, where potentially contaminated water from the Isingile was being used for irrigation (samples 291–297, Table 6). Whenever possible, a soil sample was collected from the root zone of the vegetable sample. A number of rice, bean, onion, and maize samples reported to have been grown on the Isingile *mbuga* were also purchased from Rwamagasa market (Table 7).

Recommendations for fish sampling set out by UNIDO (Veiga and Baker, 2003) were followed as closely as practicable. Fish monitoring focussed on (i) piscivores, (ii) species consumed by the local population, and (iii) food chain species with relatively restricted domains that should provide a good indication of the presence and hence availability of methyl-Hg (MeHg) in the food web.

Collection of a wide range of fish species in the Rwamagasa area was restricted by the lack of surface water, which was generally confined to ponds. Fish were collected by damming and draining ponds, by hook and line, or by seine or gill net. Fish sample locations are shown in Fig. 4. The majority of specimens collected were catfish *Clarias* spp. (5–42 cm), along with *Haplochromis* spp. (2–7 cm), and *Barbus* spp. (3–5 cm). Small specimens of piscivorous *Brycinus* were obtained at one site (Table 8). Samples of *Oreochromis niloticus* caught in Lake Victoria were also purchased from Rwamagasa market as these fish form a significant part of the diet for the local people.

Downstream, the Nikonga (Nyikonga) River site (Fig. 4) will be impacted by contamination from the Rwamagasa, Iseni, Tembomine, Nyamtonde, Nyamalulu, and Nyamalimbe artisanal mining areas and also from major historic artisanal mining activities at Nyarugusu. A small number of *Clarias* spp. and

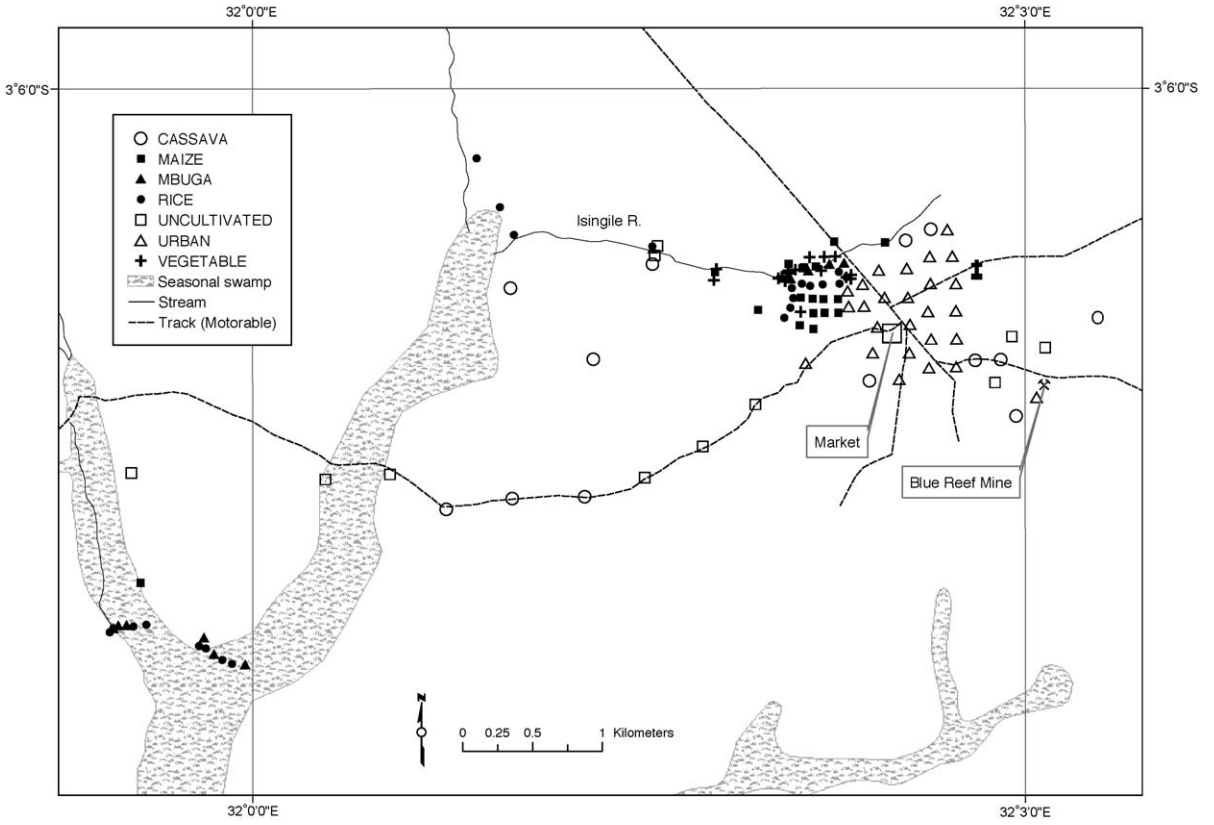


Fig. 2. Soil samples classified by land use, Rwamagasa area.

gastropods and a single specimen of *Synodontis victoriae* were collected at the Nikonga River site. Two regional background sites (Munekesi and Nyamasenga), and the actively mined Tembomine site, were also sampled for fish for comparative purposes.

Fish caught in the Malagarasi River delta and in Lake Tanganyika overnight were purchased the following day from Ilagala market; these included a range of omnivorous and piscivorous species (Table 9). Fish were also caught, by net and by hook and line, approximately 60 km upstream of the delta at Uvinza (Table 9).

Taxonomic identification and information on feeding ecology/behaviour were provided by local TAFIRI experts with reference to Eccles (1992). Examples of each species were photographed and the length and weight of each specimen recorded. Muscle tissue samples were obtained from larger specimens. Small fish (fork length<12 cm) were gutted, the head and tail removed and then washed with deionised water before being stored frozen. Where individual fish were very small (3–7 cm), composite samples comprising 2 to 5 individuals of the same species, length range and site were analysed to give an average Hg content for a species/length/site combination.

3. Sample preparation and analysis

3.1. Water, sediment, tailings, and soil

Drainage sediment, soil and tailings were prepared by BGS and analysed by ACME Analytical Laboratories, Vancouver, Canada. Waters were analysed by BGS.

Hg in filtered waters was determined by cold vapour atomic fluorescence spectroscopy (CV-AFS) to a practical detection limit of 20–30 ng/L. Water

samples were subjected to a bromination stage, prior to analysis, to break down any organo-Hg compounds. Arsenic was determined by hydride generation AFS to a practical detection limit of 0.25 μg/L. Drainage sediment, mineral processing tailings, and soils were dried at 30°C to minimise Hg loss by volatilisation. Samples were disaggregated and ground in an agate vibratory cup mill for a few seconds, split by cone and quartering, and approximately 30–50 g ground to <150 μm in an agate planetary ball mill for 30 min. Hg was determined by CV-AAS (<10 mg/kg) or ICP-ES (>10 mg/kg) following digestion in *aqua regia* (1:1:1 $cHNO_3$+ cHCl+demineralised H_2O). *Aqua regia*-soluble As, Cd, Fe, and Pb were determined by ICP-ES to practical detection limits of 2 mg/kg As, 0.5 mg/kg Cd, 0.01% Fe, and 3 mg/kg Pb. Total organic carbon (TOC) was determined using a LECO® direct combustion/infrared detection analyser to a practical detection limit of 0.02%. Recoveries of 96–102% were recorded for the ICP-ES and TOC analysis and 95% for CV-AAS Hg based on CANMET-STSD-4 (Canada Centre for Mineral and Energy Technology Stream Sediment Reference Material).

3.2. Fish and vegetables

Fish and vegetable samples were prepared and analysed by Direct Laboratory Services, Wolverhampton, UK. Homogenised fish and vegetables were macerated in a food processor to produce a fine pulp. Mercury in 150 mg of freshly macerated sample was measured directly using a LECO® AMA 254 Advanced Mercury Analyser to a reporting limit of 0.004 mg/kg. In this method, an aliquot of sample is combusted in pure oxygen and all evolved gases are passed through a gold amalgamator, which collects and pre-concentrates Hg. Mercury vapour released from the amalgamator by thermal decomposition is quantified by AAS. Recoveries ranged from 94 to 103% for BCR-422 (cod muscle) and 90–93% for BCR-060 (aquatic plant). The analytical precision (Relative Percent Difference) at concentrations greater than 0.5 mg/kg was ±2.6%.

4. Results and discussion

4.1. Water

In the Rwamagasa area, Hg in filtered water samples from the immediate vicinity of Rwamagasa do not exceed concentrations detected at the two background sites (0.04–0.05 μg/L) apart from one sample with 0.07 μg/L, located in the Isingile River about 1 km downstream of the nearest Hg amalgamation ponds (Table 1). Filtered water from a well located within Rwamagasa village, which was not used for the abstraction of drinking water, contained 0.01 μg/L Hg whilst filtered water from a Hg amalgamation pond contained 0.44 μg/L. Hg in filtered stream and river water does not exceed any of the Tanzanian Water Quality Standards (Table 1) or other water quality standards or criteria for drinking water, protection of aquatic biota or protection of human health, apart from samples from the Hg amalgamation ponds (Appleton et al., 2004). Release of some of this Hg-polluted water onto soils and into the Isingile River drainage system is inevitable, especially during the rainy season. Concentrations in

Table 1
Comparison of As and Hg concentrations in filtered water samples from the lower River Malagarasi (n=7), the Rwamagasa area drainage system (n=13), and Rwamagasa Hg amalgamation ponds (n=2) with Tanzania Water Quality Standards (concentrations in μg/L)

	Malagarasi River	Rwamagasa area—drainage system	Rwamagasa area—Hg amalgamation ponds	Tanzania Water Standards[a]		
				Drinking water	Water for domestic animals, fisheries, shell-cultures, recreation	Irrigation water
As	nd	0.87 (0.13–2.42)	0.54–1.50	na	na	na
Hg	0.02 (0.01–0.03)	0.04 (0.01–0.07)	0.43–0.45	1	1	5

nd=not determined; na=not available; Appendix: Overview of existing and future national actions, including legislation relevant to mercury 15 July, 2002 (www.chem.unep.ch/mercury/WGmeeting/revdraftappendix1-natlegislation-with-comments.doc).

[a] UNEP, Global Mercury Assessment.

Table 2
Comparison of heavy metals in drainage sediments from Background, Rwamagasa, and Nikonga R. subareas compared with Sediment Quality Criteria for the Protection of Aquatic Life (concentrations in mg/kg, except percent (%) Fe and TOC)

	Malagarasi River range	Background areas range	Rwamagasa area range	Rwamagasa area average	Nikonga River range	Sediment quality criteria[a]		
						No effects threshold	Minimal effects threshold	Toxic effects threshold
n	7	2	11	11	3			
As	1–3	1	1–16	6	1	3	7	17
Cd	<0.5	<0.5	<0.5–0.7	<0.5	<0.5	0.2	0.9	3
Hg	0.10–0.66	0.08–0.09	0.04–2.84	0.84	0.09–0.19	0.05	0.2	1
Pb	6–12	8–18	9–38	15	3–11	23	53	170
Fe	1.0–4.4	0.6–0.8	1.3–7.0	4.4	0.2–0.9	na	na	na
TOC	0.8–3.6	1.3–2.6	1.3–6.3	3.4	0.2–2.8	na	na	na

na=not applicable.
[a] Sediment Quality Criteria for Protection of Aquatic Life (Environment Canada, 1992 quoted in Haines et al., 1994).

the range 0.01–6.78 μg/L (mean 0.68 μg/L) have been reported for filtered water from rivers, streams, and domestic water ponds in the Lake Victoria goldfield (Ikingura et al., 1997).

Arsenic in filtered water samples from the Rwamagasa area (Table 1) ranged from 0.1 to 0.5 μg/L in background areas to an average of 0.97 μg/L (maximum 2.4 μg/L) in the Isingile River and associated drainage systems, 0.5–1.5 μg/L in Hg amalgamation ponds and 0.1 μg/L in the single well sample. None of the arsenic concentrations observed in these samples exceed US EPA, WHO, or EC water quality criteria (10–50 μg/L; Appleton et al., 2004). As and Hg in filtered water samples do not correlate significantly.

4.2. Drainage sediment

Drainage sediment samples collected upstream of Uvinza, on the Malagarasi River (Fig. 1), have relatively low Hg (0.17–0.24 mg/kg) compared with samples from Ilagala which range from 0.10 to 0.66 mg/kg. The Ilagala samples contain higher Fe (4.1%), TOC (3.1%), and fine (<150 μm) fraction (15–50%) compared with the Uvinza samples (1.1% Fe, 0.8% TOC, <5% fine fraction), which would partially account for the higher Hg concentrations. Possible sources of Hg include the geothermal springs at Uvinza (James, 1967; Tiercelin et al., 1993) and contamination by mercuric soap used for skin lightening (Glahder et al., 1999). "Natural" background concentrations of Hg in the fine fraction of drainage sediments reported in the literature generally range up to 0.6 mg/kg (Gustin et al., 1994; Gray et al., 1996; Babut et al., 2003; Berzas Nevado et al., 2003).

In the Rwamagasa area, Hg in drainage sediments range from 0.08 to 0.09 mg/kg at the two background sites located 4.5 and 6 km to the NW and NE of Rwamagasa. Sediments in the Isingile River impacted by Hg contamination range up to 2.84 mg/kg with an average of 0.84 mg/kg (Table 2). Hg in drainage sediment declines to less than 0.2 mg/kg in the Nikonga River, about 23 km downstream of Rwamagasa, which is surprisingly low considering that the site could be impacted by Hg contamination derived from the Rwamagasa, Iseni, Tembomine, Nyamtonde, Nyamalulu, and Nyamalimbe artisanal mining areas and also by contamination from the major historic

Table 3
Summary statistics for grouped tailings samples (concentrations mg/kg except Fe)

Sample type (number)	As	Cd	Fe (%)	Hg	Pb
Sluice box tailings (32)					
Average	24.4	0.7	4.6	6.9	21.4
Minimum	2.0	0.3	2.3	0.2	1.5
Maximum	46.0	6.1	7.5	39.0	101.0
Tailings tips (13)					
Average	18.7	2.8	4.1	9.5	11.3
Minimum	6.0	0.3	2.7	0.7	1.5
Maximum	26.5	15.7	5.6	56.5	34.0
Hg pond tailings (10)					
Average	34.1	3.9	4.4	101.1	31.9
Minimum	8.5	0.3	2.6	28.5	2.3
Maximum	62.5	22.1	5.6	193.0	95.0

artisanal mining activities at Nyarugusu. Hg correlates significantly (p=0.05) with Cu, Fe, and As, reflecting the gold mineralization geochemical association and with TOC (p=0.10) due to adsorption.

Hg exceeds the Toxic Effects Threshold for the Protection of Aquatic Life by a factor of up to 3 in drainage sediments in the Rwamagasa area (Table 2) but declines below the Threshold about 2 km downstream of the mineral processing sites. The toxic effects thresholds for As, Cd, and Pb are not exceeded in the bottom sediments sampled from the Rwamagasa area (Table 2).

Methylation of inorganic Hg could take place during the dry season in ponds that remain along the course of the River Isingile and also in irrigation channels; and, in the wet season, on the flooded seasonal swamp areas of the *mbugas* and rice paddy fields of the Nikonga drainage basin (Fig. 2).

4.3. Mineral processing waste material (tailings)

Similar levels of Hg occur in samples from historic tailings piles (mean 5 mg/kg) and recent sluice box tailings (mean 3 mg/kg; Table 3 and Fig. 3). This suggests that both types of tailings have been contaminated with Hg as a result of reprocessing tailings from amalgamation ponds (mean 86 mg/kg). Reprocessing and inappropriate storage of tailings from the amalgamation ponds is undoubtedly a major potential source of environmental Hg contamination in the Rwamagasa area. Hg concentrations in the range 0.28–31.15 mg/kg (mean 10.27 mg/kg) have

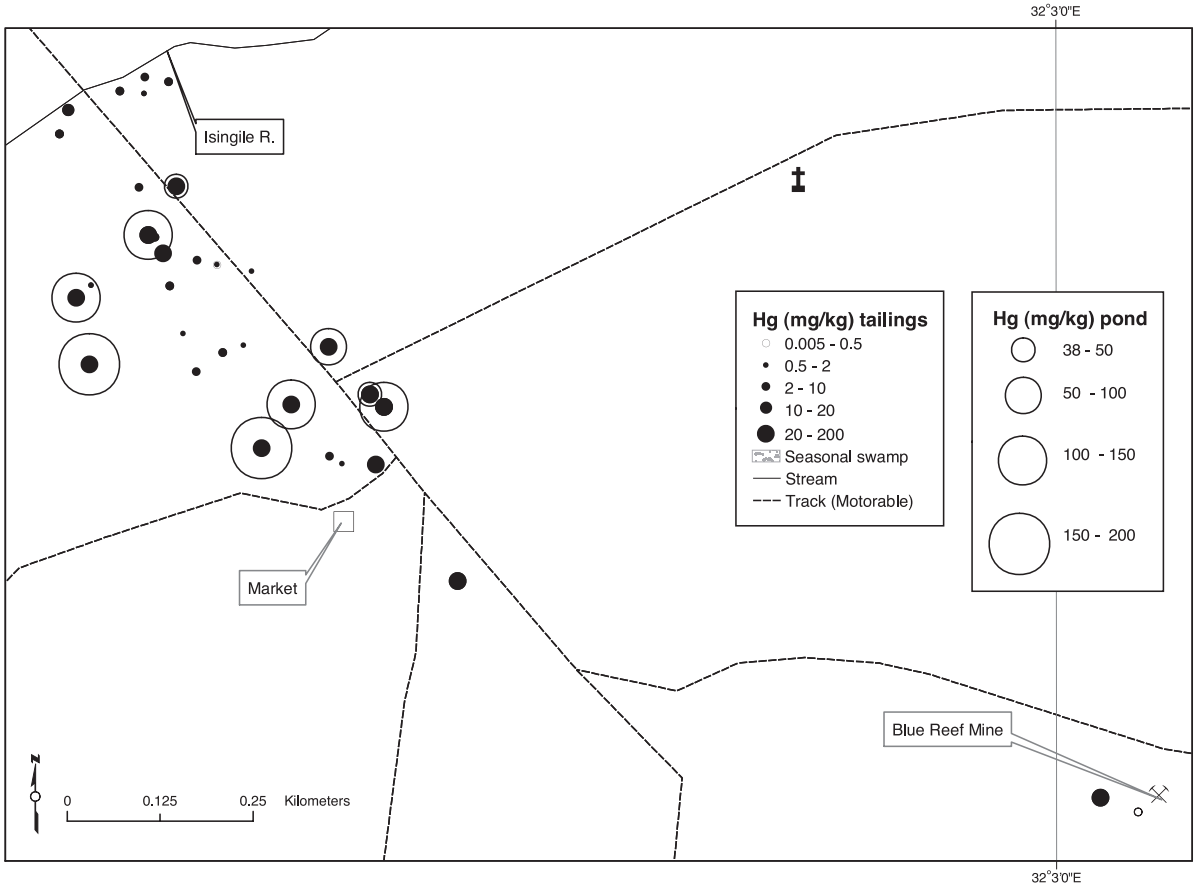


Fig. 3. Hg (mg/kg) in tailings and amalgamation ponds, Rwamagasa area.

been reported for gold ore tailings in the Lake Victoria goldfield (Ikingura et al., 1997).

4.4. Soil

Generally low concentrations of Hg occurred in most of the cassava, maize, rice, *mbuga*, and uncultivated (rural) soils whereas higher concentrations occur in the urban, some *mbuga* and vegetable plot soils (Fig. 4). Some of this Hg is possibly derived from airborne transport and deposition of Hg released during the burning of amalgam, although this has not been verified. High Hg occurs in the *mbuga* and vegetable plot soils where these appear to be impacted by Hg-contaminated water and sediment derived from mineral processing activities located on the southern side of the Isingile River (Fig. 5).

Mercury exceeds (1) the Canadian Soil Quality Guideline for agricultural soils (6.6 mg/kg) in three samples and (2) the UK soil guideline value for inorganic Hg for allotments (8 mg/kg; Environment Agency, 2002) in two samples (Tables 4 and 5). The proposed Dutch Intervention value (SRC—"serious risk concentration") for inorganic Hg (36 mg/kg; RIVM, 2001); the USEPA soil ingestion Soil Screening Level (SSL) for inorganic Hg (23 mg/kg); the USEPA SSL for inhalation of volatiles (10 mg/kg; USEPA, 1996); the Dutch proposed human health SRC of 210 mg/kg and the USEPA generic SSL for plant uptake (270 mg/kg; USEPA, 1996) are not exceeded in any soil samples. Cadmium exceeds the UK soil guideline value for allotments (2 mg/kg) in one urban soil sample (Tables 4 and 5). The Dutch SRCs for human health (24–28 mg Cd/kg) and the USEPA SSLs for soil uptake (400–622 mg Pb/kg; USEPA, 1996) are not exceeded in any of the samples collected. Arsenic exceeds the Canadian Soil Quality Guideline for agricultural soils (12 mg/kg) in nine agricultural and urban soils and exceeds the UK soil guideline value for inorganic As for allotments (20 mg/kg; Environment Agency, 2002) in five samples of maize, *mbuga*, vegetable plot, and urban soils. High Hg concentrations (1.8–4.3 mg/kg) in the top 10–20 cm of two soil profiles decline sharply to background levels (0.02–0.06 mg/kg) at greater depths in parallel with TOC which declines from 1.5–3.8% in the top 20 cm to 0.6–1.1% at greater depths (Appleton et al., 2004). Hoeing will tend to cause homogenisation of Hg contamination within the root zone.

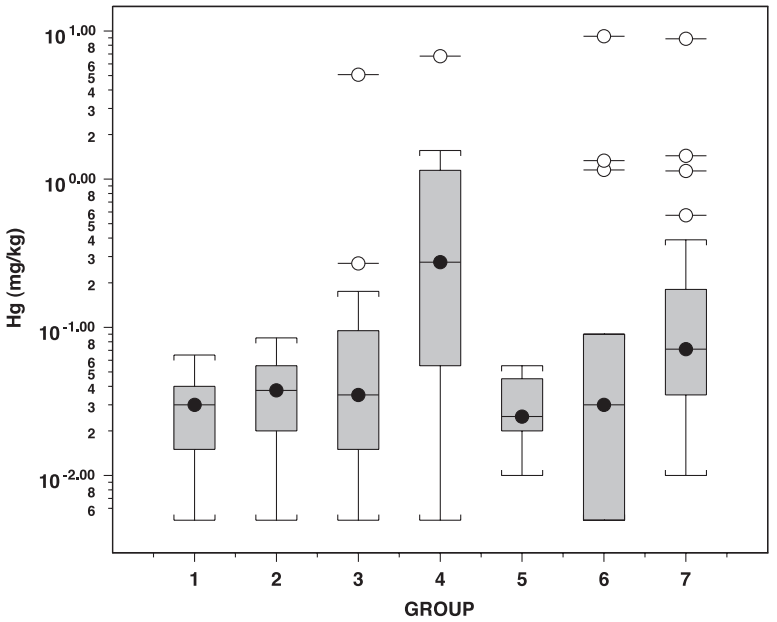


Fig. 4. Hg (mg/kg) in <2 mm soil samples classified by land use [Group (no. of samples): 1=cassava (13), 2=maize (18); 3=rice (25); 4=vegetables (17); 5=uncultivated (11); 6=*mbuga* (13); 7=urban (26)].

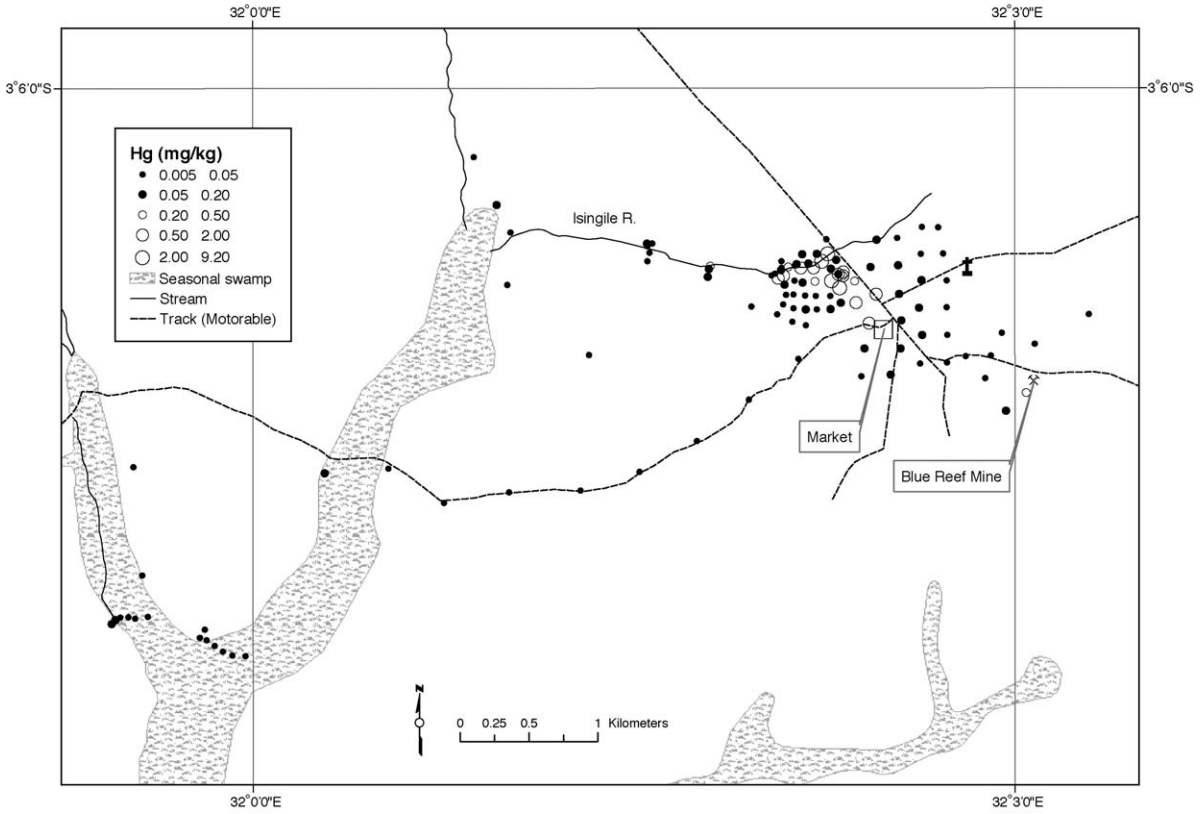


Fig. 5. Hg (mg/kg) in soils, Rwamagasa area.

In addition to the determination of Hg, soil samples were analysed for organic matter and *aqua regia*-soluble Fe in order to assess the impact of adsorption onto organic matter in the organic, clay-rich vertisols of the *mbuga* areas and Fe–Al hydroxides in the ferrallitic soils (ferric luvisols and ferric acrisols; FAO classification) that characterise interfluves underlain by 'greenstone' belt rocks. Hg correlates significantly (p=0.05) with Fe but not with TOC (Appleton et al., 2004).

4.5. Agricultural crops

The varying water requirements of the different vegetable crops govern their distribution in the Rwamagasa area. Maize, cassava, sweet potatoes, and bananas are cultivated on interfluves and in gardens adjacent to dwellings, whilst onions, tomatoes, yams, cabbage, spinach, peppers, and beans are cultivated on the irrigated plots bordering the Isingile River. Paddy rice is cultivated on the seasonally

Table 4
As, Cd, Hg, and Pb (mg/kg) in surface soils from the Rwamagasa area classified by land use

	Cassava	Maize	*mbuga*	Rice	Uncultivated (rural)	Urban	Vegetables
Count	13	18	13	25	11	26	17
As	1–12	1–22	1–23	1–10	1–10	1–67	1–31
Cd	0.3	0.3	0.3–1.3	0.3–1.1	0.3	0.3–6.2	0.3–1.1
Hg	0.005–0.07	0.005–0.09	0.005–9.2	0.005–5.1	0.010–0.06	0.010–8.9	0.005–6.8
Pb	6–13	2–11	4–14	2–15	5–12	2–16	4–15

Table 5
Soil quality guideline and limit values for As, Cd, Hg, and Pb (concentrations in mg/kg)

	Canadian human health soil quality guidelines			UK soil guideline values[a]			
	Agricultural, residential/parkland	Commercial	Industrial	Residential with plant uptake	Residential without plant uptake	Allotments	Commercial /industrial
As	12	12	12	20	20	20	500
Cd	14	49	2100	2	30	2	1400
Hg	6.6	24	50	8	15	8	480
Pb	140	260	740	450	450	450	750

[a] Environment Agency (2002).

flooded *mbuga* areas. Hg in vegetable and grains samples collected from agricultural areas potentially impacted by Hg contamination are mainly below the detection limit of 0.004 mg/kg Hg with concentrations of 0.007 and 0.092 mg/kg Hg recorded in two yam samples and 0.035 mg/kg Hg in one rice sample (Table 6). A positive correlation between Hg in agricultural crops and soil was not detected during the present survey (Table 6). Hg in beans, onions, and maize samples purchased at Rwamagasa market were below the detection limit (<0.004 mg Hg/kg) whereas two dehusked rice samples contain 0.011 and 0.013 mg/kg Hg (Table 7). It is possible that dehusked rice and other vegetables in the market will be contaminated by Hg vapour derived from amalgam burning within the urbanised area of Rwamagasa.

The concentrations of Hg in rice are similar to those recorded for rice grown on the highly contaminated soils of the Naboc irrigation system in the Philippines (average 0.016 mg/kg, range 0.008 to 0.050 mg/kg Hg wet weight (ww); Appleton, 2000). Machiwa et al. (2003) reported similar concentrations in rice grown on Hg-contaminated ground at Saragurwa (0.04 mg/kg) with much higher concentrations at Nyarugusu (0.09 mg/kg), Nungwe (0.13 mg/kg), Nyangalamila (0.25 mg/kg), and Lwamagasa (Rwamagasa, 0.29 mg/kg). Hg concentrations recorded by Machiwa et al. (2003) are unusually high in relation to Hg in soils and sediments especially when compared with data for the Quingzhen and Wanshan areas in China (Horvat et al., 2003). Machiwa et al. (2003) recorded 1.42 mg/kg (ww) in a yam sample from Samina, which is more than an order of magnitude greater than the maximum recorded during the present survey (0.092 mg/kg).

Table 6
Hg in vegetable and grain samples with associated soil sample

Number	Description	Hg (mg/kg) in vegetable or grain	Hg (mg/kg) in soil	Site location
105	Yam	0.007	0.67[a]	Near Tembomine
110	Yam	0.092	0.66	Adjacent to
111	Maize	<0.004	0.66	amalgamation
112	Cabbage	<0.004	0.66	pond, approx.
113	Onions	<0.004	0.66	480 m to NNW of Rwamagasa market
117	Rice	0.035	0.12	Approx. 590 m NNW of Rwamagasa market
291	Onion	<0.004	0.05	Vegetable gardens
292	Yam	<0.004	1.56	djacent to Isingile
293	Cabbage	<0.004	0.005	R., approx. 850 m
294A	Beans Fresh	<0.004	0.275	NW of Rwamagasa
294B	Beans Fresh	<0.004	0.275	market
295	Beans Fresh	<0.004	0.275	
296	Tomatoes	<0.004	0.085	
297	Maize	<0.004	0.055	

[a] Irrigation channel sediment.

Table 7
Hg in vegetable and grain samples from Rwamagasa market

Number	Description	Hg (mg/kg)
303	Maize Dry	<0.004
304	Rice	0.011
305	Rice	0.031
306	Onions	<0.004
307	Dry Green Beans	<0.004
308	Dry Green Beans	<0.004
309	Dry White Beans	<0.004
310	Dry Mixed Beans	<0.004

4.6. Fish

Ideally, muscle tissue data should be considered separately from data for whole fish from which the head, tail, and guts have been removed. However, Coetzee et al. (2002) reported no significant difference in the bioaccumulation of Cu, Mn, Pb, Cr, Ni, Fe, or Al in skin compared with muscle of South African *Clarias* spp., although Zn was 2 to 3 times higher in skin compared with muscle tissue. No comparable data are readily available for Hg. Adequate numbers of muscle tissue and whole fish samples for the same species were obtained at two sites (*Clarias alluadi* at Nyamsenga and *Clarias gariepinus* at Pond 4). Hg/length ratios (Table 8) are similar, so whole fish and muscle tissue samples from the same site are treated as one population in this study. Comparisons are drawn with Lake Victoria Environmental Management Project (LVEMP) fish data transformed from dry to wet weight basis using mean conversion factors of 0.290 (*Lates niloticus*), 0.256 (*Oreochromis niloticus*), and 0.242 (*Clarias gariepinus*; Machiwa et al., 2003).

The relationship between Hg and length in *Clarias* confirms the expected increase in Hg with size, and is best demonstrated by the Lake Victoria (LVEMP), Tembomine and Rwamagasa Ponds 4 and 6 data sets (Fig. 6). The 10-cm standardized Hg concentrations increase from about 0.01 mg/kg for Lake Victoria (LVEMP) and River Malagarasi (Ilagala) to 0.07 mg/kg for the Rwamagasa 'background' sites, 0.2 mg/kg for Rwamagasa Ponds 4 and 6, 0.26 mg/kg for Tembomine, and about 1.6 mg/kg for Rwamagasa Ponds 1, 2, and 5. As there is no record of artisanal gold mining upstream from the Rwamagasa 'background' sites, it appears that these *Clarias* are probably influenced by airborne Hg contamination. At other sampling sites, insufficient samples over a wide enough size range were available to define Hg/length relationships for *Clarias*. In the Rwamagasa area, this increase in Hg concentrations broadly reflects the

Table 8
Total Hg concentrations in fish and invertebrates in the Rwamagasa subarea

Site	Species[a]	Feeding behaviour[b]	Sample type[c]	Mean length (cm)	Mean (min–max) Hg (mg/kg)	Hg (μg/kg)/length (cm) ratio	*n*
Market	*O. niloticus*	O–D	MT	17.1	0.009 (0.002–0.031)	0.5	5
Munekesi	*C. gariepinus*	O–B	MT	20.1	0.119 (0.048–0.199)	5.9	4
	C. gariepinus	O–B	WF	13.6	0.150 (0.138–0.161)	11.0	2
Nyamsenga	*C. alluadi*	O–B	MT	16.1	0.134 (0.078–0.231)	8.3	3
	C. alluadi	O–B	WF	9.3	0.083 (0.044–0.115)	8.9	11
Tembomine	*C. gariepinus*	O–B	MT	22.7	0.792 (0.173–1.84)	34.9	25
Pond 1	*Barbus* spp.	I	WF	5.4	1.05 (0.684–1.53)	194.4	5
	C. gariepinus	O–B	MT	14.2	1.61 (1.24–1.97)	113.3	2
Pond 2	*C. gariepinus*	O–B	WF	6.7	1.67	249.3	1
	Haplochromis spp.	O–PL	WF	3.0	2.06 (0.995–2.65)	686.7	5
Pond 4	*C. gariepinus*	O–B	MT	17.3	0.336 (0.163–0.637)	19.4	7
	C. gariepinus	O–B	WF	11.1	0.222 (0.092–0.510)	20.0	12
	Haplochromis spp.	O–P	WF	4.7	0.323 (0.195–0.443)	29.1	4
Pond 5	*C. gariepinus*	O–B	WF	11.9	0.779 (0.189–1.64)	65.5	4
Pond 6	*Barbus* spp.	I	WF	4.2	0.301 (0.285–0.318)	71.7	4
	Brycinus spp.	P	WF	6.7	0.338 (0.206–0.398)	50.4	6
	C. alluadi	O–B	WF	8.5	0.267 (0.187–0.431)	31.4	4
	C. gariepinus	O–B	WF	13.4	0.538 (0.339–0.792)	40.1	5
	Haplochromis spp.	O–P	WF	3.3	0.167 (0.145–0.189)	50.6	2
Nikonga R.	*C. alluadi*	O–B	WF	8.6	0.071 (0.055–0.084)	8.3	5
	Synodontis victoriae	O–B	WF	4.4	0.265	60.2	1
	Gastropoda	H	MT	4.1	0.040 (0.019–0.069)	9.8	5

[a] C=*Clarias;* L=*Lates*; O=*Oreochromis*.
[b] B=Benthic; D=Detritivore; H=Herbivore; I=Insectivore; O=Omnivore; P=Piscivore; PL=Planktivore.
[c] MT=muscle tissue; WF=whole fish (guts, head, and tail removed).

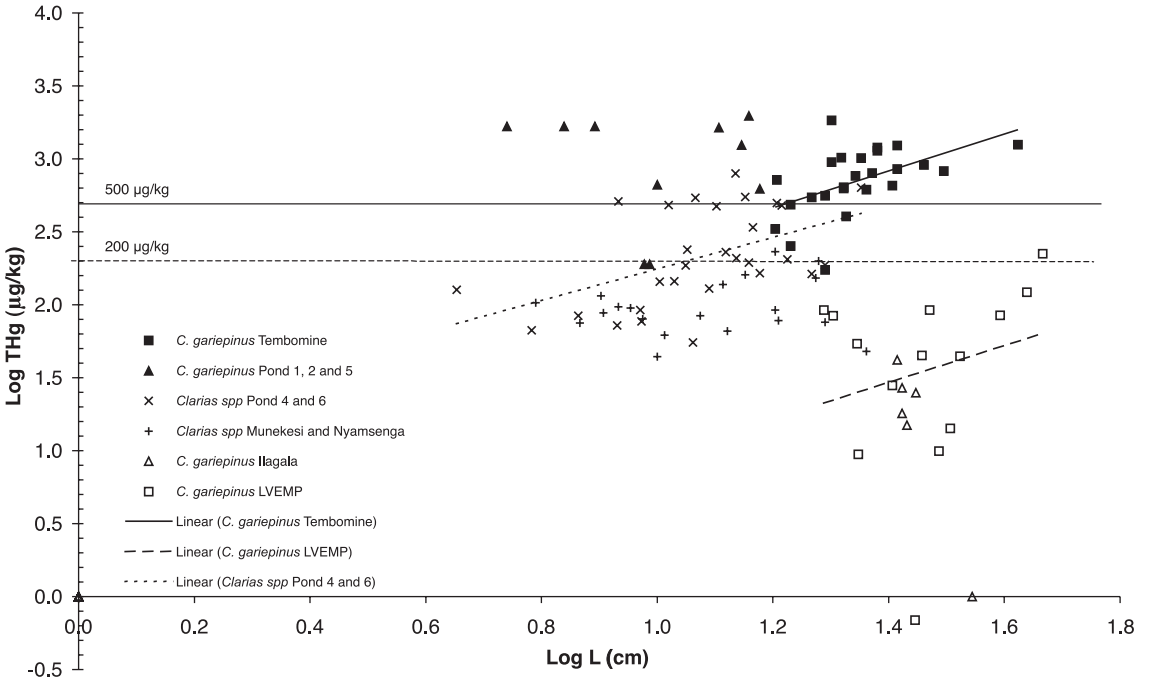


Fig. 6. Hg (µg/kg) related to length (cm) in *Clarias* spp. (LVEMP data from Machiwa et al., 2003).

level of Hg contamination in sediments (Fig. 7) and significant correlations occur between mean sediment Hg and mean Hg in *Clarias* (p=0.03) and between sediment Hg and the *Clarias* Hg/length ratio (p=0.05; Fig. 8). *Clarias* are benthic feeders and their relatively high tissue Hg concentrations are probably explained by this behaviour. Hg concentrations as high as those for fish from Ponds 1, 2, 4, and 6 have been reported elsewhere, for example in *Clarias* collected from the Isagana (Isanga) River, which is impacted by Hg from the Bulyankulu and Katende Mines, and also from Winam Gulf in Kenya (Campbell et al., 2003a), although based on their weights (no length data were reported by Campbell et al., 2003a), the fish were much larger than those in the present study. van Straaten (2000a) reported a muscle tissue concentration of 2.55 mg/kg Hg for a single specimen of *Clarias* caught in a tailings pond in the Kahama District in northern Tanzania.

For *Lates*, *Brycinus*, and *Hydrocynus* (piscivores), *Barbus* (insectivores), and *Haplochromis* (planktivores; Fig. 9 and Tables 8 and 9), Hg/length relationships show the 10-cm standardized Hg concentrations generally increase from about 0.006 mg/kg for Lake Victoria (LVEMP) and the River Malagarasi–Lake Tanganyika subarea (Ilagala and Uvinza), to 0.5 mg/kg for Rwamagasa Ponds 4 and 6, and about 3.5 mg/kg for Rwamagasa Ponds 1 and 2. Standardized Hg concentrations are somewhat higher than for *Clarias*, reflecting the higher trophic levels these fish occupy, especially the piscivorous species. The linear Hg/length relationship for the LVEMP data set confirms the expected increase in Hg with size (Fig. 9).

Haplochromis collected from Rwamagasa Pond 2 had the highest Hg levels (2.06 mg/kg) and highest Hg/length ratios of all the four species present in Ponds 1 and 2 (Table 8). In comparison, the highest tissue concentration found in large *Haplochromis* from the Hg-contaminated Mara and Mwanza regions of Lake Victoria was 0.420 mg/kg (Machiwa et al., 2003); Campbell et al. (2003b) recorded 0.005 mg/kg for a single small specimen of *Haplochromis* caught in Lake Naivasha. *Barbus* in Pond 1 had an average muscle tissue Hg concentration of 1.05 mg/kg. Concentrations up to 0.1 mg Hg/kg have been recorded in larger specimens of *Barbus* collected from Lakes Baringo and Naivasha (Campbell et al.,

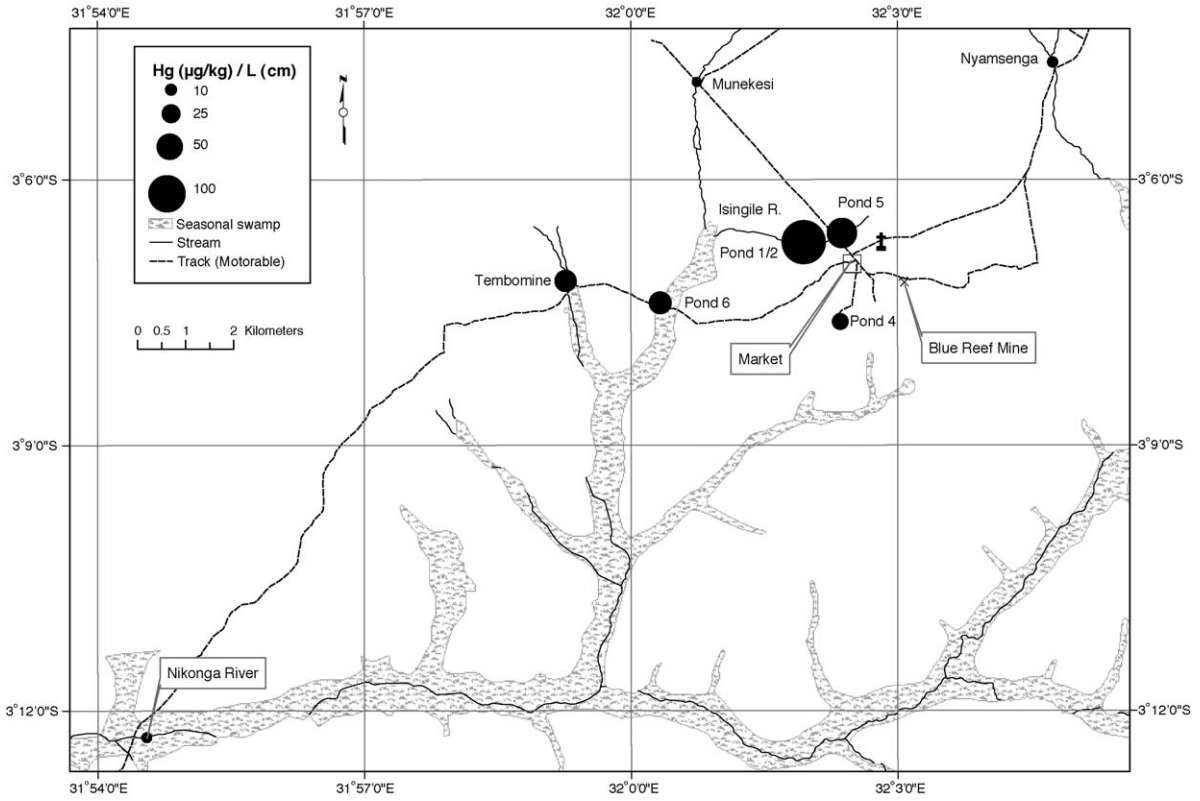


Fig. 7. Fish sample locations and Hg/length (L) ratios for *Clarias* spp., Rwamagasa area.

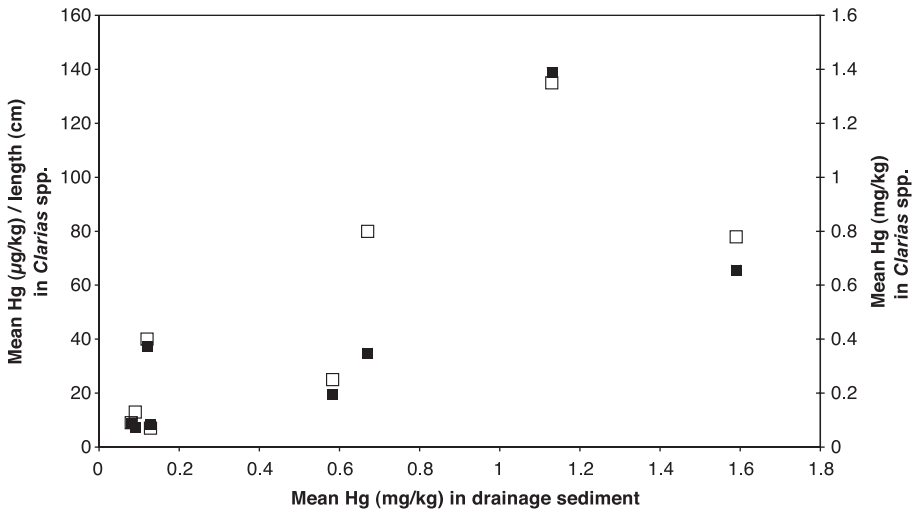


Fig. 8. Relationship between Hg (mg/kg) in drainage sediment, mean Hg (mg/kg) (□) and mean Hg (µg/kg)/length (cm) ratio (■) for *Clarias* spp. from the Rwamagasa area.

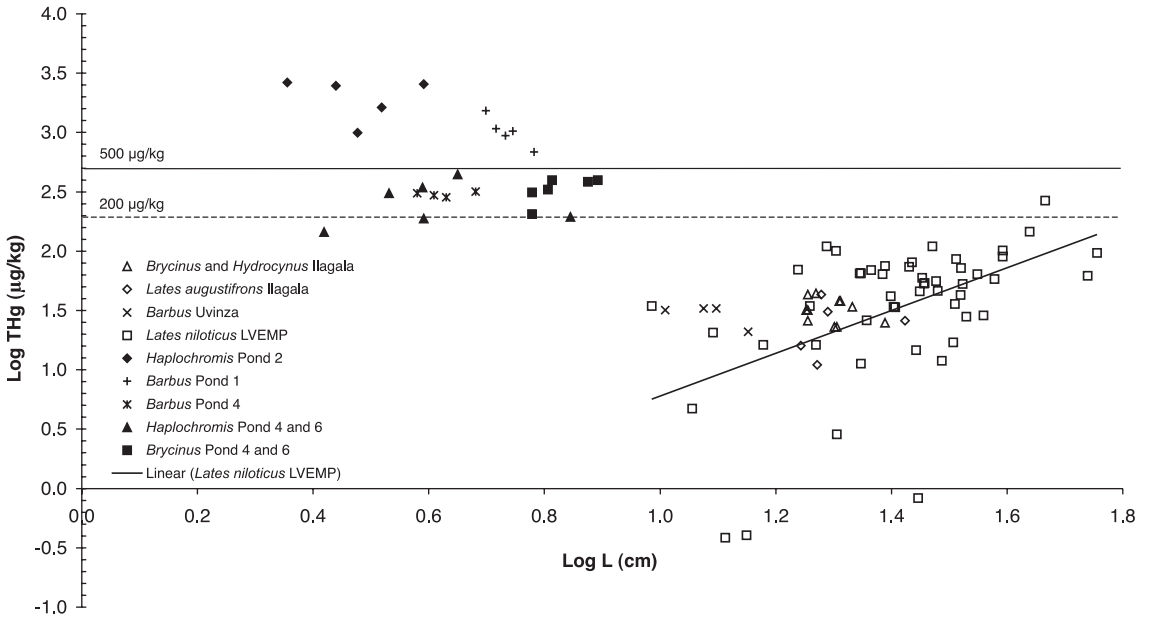


Fig. 9. Hg (µg/kg) related to length (cm) in piscivores, insectivores, and planktivores from the Rwamagasa area, River Malagarasi–Lake Tanganyika (Ilagala, Uvinza), and Lake Victoria (LVEMP, Machiwa et al., 2003).

2003b), whereas maximum concentrations of <0.020 mg/kg were recorded for large insectivorous African tetra collected from Nungwe Bay and Mwakitolyo Mine/Mwanza (Ikingura and Akagi, 1996; Kahatano et al., 1997).

According to other studies in this region, only piscivorous fish such as *Lates* might be expected to contain Hg concentrations as high as those in *Barbus*, *Haplochromis*, and *Clarias* at the sites closest to the mining activities in Rwamagasa. Tissue concentrations up to 1.2 mg/kg have been reported in large *Lates* in the Mwanza Gulf (Campbell et al., 2003a). Conversely, very low Hg concentrations (mean Hg 0.005–0.040 mg/kg) were recorded in *Lates* from potentially Hg-contaminated reservoirs in Tanzania (Ikingura and Akagi, 2003). The Hg levels found in

Table 9
Total Hg concentrations in fish in the Lake Tanganyika sub-area

Site	Species[a]	Feeding behaviour[b]	Sample type[c]	Mean length (cm)	Mean and range Hg (mg/kg)	Hg (µg/kg)/length (cm) ratio	*n*
Uvinza[d]	*Barbus tropidolepsis*	I	MT	12.2	0.030 (0.021–0.033)	2.5	4
	O. tanganicae	O–D	MT	12.1	0.046 (0.014–0.074)	3.8	4
	Disticodus spp.	O–H	MT	2.25	0.026	11.6	1
Ilagala Market[e]	*Auchenoglanis occidentalis*	O–D	MT	23.3	0.014 (0.005–0.034)	0.6	5
	Brycinus rhodopleura	P	MT	20.1	0.028 (0.025–0.032)	1.4	3
	C. gariepinus	O–B	MT	28.2	0.022 (0.002–0.042)	0.8	6
	Hydrocynus vittatus	P	MT	19.7	0.034 (0.023–0.044)	1.7	8
	L. augustifrons	P	MT	20.2	0.025 (0.011–0.043)	1.2	5
	O. tanganicaea	O–D	MT	14.0	0.013 (0.007–0.021)	0.9	5

[a] See Table 8.
[b] See Table 8.
[c] See Table 8.
[d] Fish from Malagarasi River.
[e] Fish from Malagarasi River Delta–Lake Tanganyika.

predatory *Brycinus* in the moderately impacted Pond 6 suggest that levels are elevated compared with more omnivorous fish such as *Clarias*. However, more data are needed to establish the extent to which piscivorous fish in waters impacted by mineral processing activities in Rwamagasa area are contaminated with Hg.

Downstream of Rwamagasa, gastropods from the Nikonga River site (Table 8) contained low Hg whilst Hg/length ratios for *C. alluadi* from the same site were comparable to *Clarias* from the two 'background' sites (Table 8). This is a reflection of the low level of environmental Hg contamination this far downstream of Rwamagasa. *Synodontis* is a relatively rare benthic feeder and the specimen from the Nikonga River had a relatively high Hg/length ratio (Table 8). The reason for this is not clear; Machiwa et al. (2003) reported Hg concentrations of <0.080 mg/kg in much larger specimens of *Synodontis* from Lake Victoria.

Mean tissue Hg concentrations in piscivorous *Lates*, *Brycinus*, and *Hydrocynus* (0.025, 0.028, and 0.034 mg/kg, respectively) from the Malagarasi River–Lake Tanganyika area (Ilagala market) are not markedly different to Hg concentrations found in *Clarias* (0.022 mg/kg) and *Barbus* (0.030 mg/kg), or in *Oreochromis* (Table 9). These data are consistent with previously reported data for these types of fish in this region (Campbell et al., 2003a,b; Ikingura and Akagi, 1996; Machiwa et al., 2003; Sindayigaya et al., 1994). *Oreochromis* are detritivorous/herbivorous species that occasionally consume invertebrates, and smaller *Oreochromis* and other tilapia species. Data for *Oreochromis tanganicae* from the River Malagarasi–Lake Tanganyika subarea broadly follow the Hg/length regression for Lake Victoria (Fig. 10), whereas *Oreochromis niloticus* from Rwamagasa market (assumed to come from Lake Victoria) have lower Hg/length ratios (Table 8). Lower Hg/length ratios characterise *O. tanganicae* from Ilagala (reported to originate from Lake Tanganyika) compared with *O. tanganicae* from Uvinza (Table 9). This may reflect higher sediment Hg in the River Malagarasi compared with Lake Tanganyika.

Many of the fish samples from Rwamagasa (Table 8 and Figs. 7 and 9) exceed quality guidelines including those for Canada and Brazil (0.5 mg THg/kg); Finland, Sweden, and Japan (1 mg/kg);

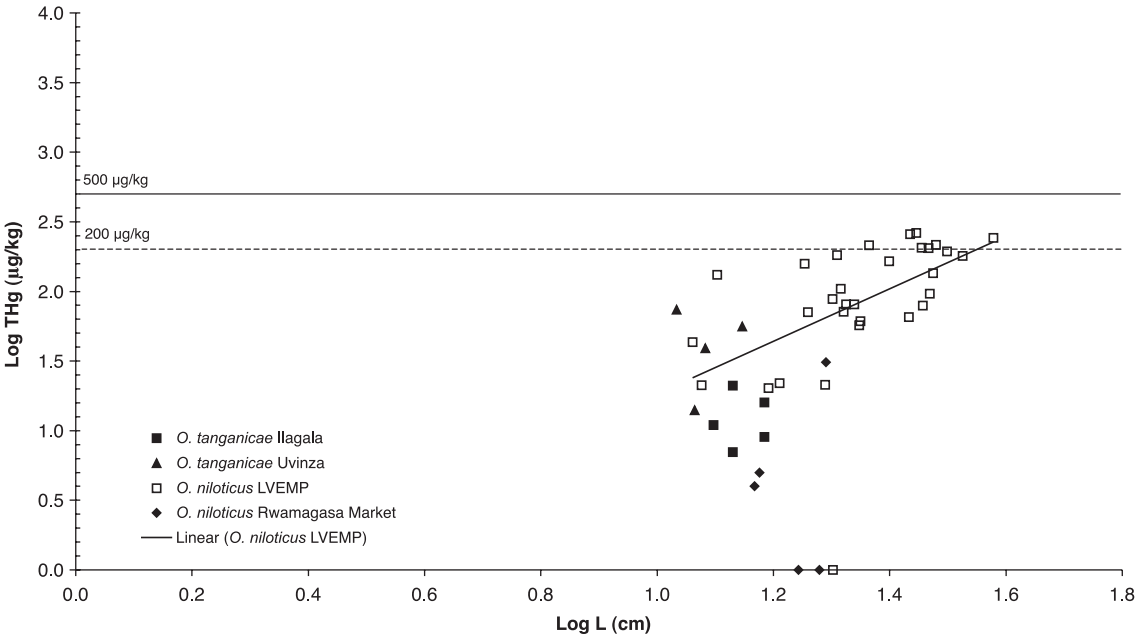


Fig. 10. Hg (µg/kg) related to length (cm) in *Oreochromis* spp. from the Rwamagasa area, River Malagarasi–Lake Tanganyika (Ilagala), and Lake Victoria (LVEMP, Machiwa et al., 2003).

and the European Community (1 mg/kg for predatory fish and 0.5 mg/kg for nonpredatory species). The WHO (1989) has adopted a safety guideline value of 0.5 mg MeHg/kg and recommended a limit of 0.2 mg/kg for vulnerable groups (frequent fish consumers, pregnant women, and children under 15 yrs old). Muscle tissue Hg of all fish collected from the River Malagarasi–Lake Tanganyika subarea are well below these guideline levels (Table 9 and Figs. 7, 9, and 10). This suggests that whilst the fish in the immediate Rwamagasa area were at the time of this survey severely affected by Hg contamination, the southward dispersion of Hg from the Rwamagasa and adjacent artisanal gold mining areas appears to be relatively restricted and it appears, on the basis of the new data reported here, that the impact on fish in the Malagarasi River and Lake Tanganyika is negligible. The extensive swamps and flooded grasslands between Rwamagasa and Lake Tanganyika (Fig. 1) will tend to inhibit the dispersion of inorganic Hg, although they may also act as a sink in which Hg that is available is methylated.

4.7. Exposure to environmental mercury

4.7.1. Drinking water

None of the filtered water samples collected from the river network, or associated drainage ponds exceeded the WHO or local Tanzanian guideline values of 1 μg/L Hg for drinking water. Whilst this suggests that mineral processing operations have not contaminated local surface waters and shallow groundwaters, it does not indicate whether drinking water from shallow wells used by the local people has been contaminated. Water from amalgamation ponds contained up to 0.45 μg/L, which highlights the need for careful management of wastewaters from these ponds and monitoring of any nearby drinking water supplies. More extensive monitoring of drinking water sources, which was not the focus of the current investigations, should be considered as a component of any subsequent follow up work.

4.7.2. Locally produced rice, maize, cassava, and vegetables

The maximum likely dietary intake of rice by the local residents in the Rwamagasa area is estimated to be 300 g per person per day, although this may be an overestimate as the local people also usually consume cassava and maize. The average Hg concentration recorded for samples of rice grain grown in the study area was 0.026 μg/g (ww), so the maximum amount of Hg entering the body due to rice consumption is 7.8 μg Hg/day, equivalent to 0.055 mg/week. This value is much lower than the Provisional Tolerable Weekly Intake (PTWI) of 0.3 mg for Hg in the diet set by the WHO and the FAO, which is equivalent to 0.86 μg/kg body weight (bw)/day for a typical adult (50 kg). Of this amount, the maximum intake of MeHg should be no more than 0.4 μg/kg bw/day. If 50% of the Hg in Rwamagasa rice is MeHg (see Horvat et al., 2003), then the total weekly MeHg burden from rice would be 27.5 μg MeHg equivalent to only 0.079 μg/kg bw/day.

The maximum total Hg intake for consumers of 'average' Rwamagasa rice is also lower than the Japanese safe guideline limit (0.036 mg/day for an adult weighing 50 kg; Nakagawa and Yumita, 1998) as well as the Provisional Tolerable Daily Intake (PTDI) for adults (0.47μg/kg bw/day) and for pregnant women and children (0.2 μg/kg bw/day) in Canada. However, individuals consuming Rwamagasa rice at the upper limit of the Hg concentration range recorded in the current survey (0.035 μg/g) would have a daily intake of up to 0.2 μg/kg bw/day, which is equal to the Canadian PTDI for children and pregnant women. These are likely to be maximum inputs because most people in the Rwamagasa area will also consume cassava and maize, which are grown on soils with low Hg concentrations. No information is available on the relative proportions of rice, maize, cassava, and yams consumed in the area (Wagner, 2003; Böse-O'Reilly et al., 2004), so it is difficult to calculate Hg inputs from each of these staple food sources. Yams are generally relatively expensive and, on average, constitute about 10% of dietary intake from staple crops. An individual consuming 30 g/day of yam with the highest Hg concentration recorded in the current survey (0.09 mg/kg) would have a daily intake from yam of 0.05 μg/kg bw/day.

4.7.3. Fish

Data from the Rwamagasa medical assessment (Böse-O'Reilly et al., 2004) indicate that 4% of the 252 cases ate fish once a month, 69% ate fish at least

once a week, and 27% ate fish at least once a day. Of those that ate fish at least once a day, 78% ate only one fish meal a day, 15% twice a day, and 7% three fish meals a day. The vast majority of cases principally ate tilapia (*Oreochromis* spp.), Nile perch (*Lates* spp.), and dagaa (dagan; *Haplochromis* spp. and equivalents). Catfish (kambare, mumi; *Clarias* spp.) was eaten by only 9% of the cases who ate fish at least once a week and only 7% of cases who ate more than one fish meal a day. Ninety-eight percent of cases stated that the fish they consumed came from an area distant from the mining-impacted area or from the market, so the most likely source is Lake Victoria. No cases mentioned that catfish from mining-impacted areas were eaten, although during the present study, at least one family living outside Rwamagasa village reported that they ate catfish from the Isingile River.

Consumption of 250 g Nile perch, 500 g tilapia, and 250 g of catfish each week would result in an intake of 16 μg Hg/week for residents of Ilagala, 66 μg Hg/week for people depending totally on fish from Mara and Mwanza regions of Lake Victoria, 39 μg Hg/week for people in the Rwamagasa background area consuming tilapia and Nile perch from Lake Victoria and catfish from the local streams, and 117 μg Hg/week for people in the Rwamagasa area consuming tilapia and Nile perch from Lake Victoria and catfish from mining-impacted streams (Tables 10 and 11). These inputs related to fish consumption are well below the Provisional Tolerable Weekly Intake (PTWI) of 300 μg for total Hg in the diet recommended by the Joint FAO/WHO Expert Committee on Food Additives (JECFA; FAO/WHO, 2003). If 80% of the total Hg in the fish is MeHg, then the weekly intake by people consuming tilapia and Nile perch from Lake Victoria and catfish from mining-impacted streams is approximately 94 μg MeHg, which is approximately 50% of the JECFA PTWI of 200 μg for MeHg. In the relatively unlikely situation where people were consuming solely catfish from mining-impacted streams, these cases would have a weekly intake of 423 μg THg/week and 338 μg MeHg/week (Table 11), which is about 50% greater than the JECFA PTWIs. This is unlikely to occur with people living in Rwamagasa but may occur occasionally with people living close to the Isingile River and near Tembomine, for example.

4.7.4. Inadvertent and deliberate ingestions of soil and dust

Whilst exposure via food and drinking water have traditionally been considered to be major sources of exposure to potentially toxic elements such as Hg, the development of risk assessment methodologies for contaminated sites and mine workings has highlighted the importance of the inadvertent and deliberate ingestion of soils and dusts (e.g., Ferguson et al., 1998; Williams et al., 1998). For example, in deriving the UK's guideline values for Hg in soil, approximately 80% of the total exposure is apportioned to the inadvertent ingestion of contaminated soils and dusts (Environment Agency, 2002).

Table 10
Hg (μg/kg ww) in fish from the Rwamagasa area, Malagarasi River–Lake Tanganyika (Ilagala), and Lake Victoria: data for Hg exposure estimates (see Table 11)

Species	Source of fish	No.	Hg (μg/kg)		
			Range	Average	Geomean
Lates spp. (Nile perch)	Ilagala	5	11–43	24	23
	Lake Victoria[a]	36	0.4–97	46	31
Oreochromis spp. (tilapia)	Ilagala	5	7–21	28	12
	Lake Victoria[a]	30	20–263	124	97
	Lake Victoria (Rwamagasa market)	5	2–31	9	5
Clarias spp. (catfish)	Ilagala	6	2–42	22	16
	Rwamagasa background	7	48–231	127	110
	Rwamagasa mining impacted	9	163–1970	618	423
	Lake Victoria[a]	14	0.7–223	65	35
Haplochromis spp. (dagaa)	Rwamagasa mining impacted	11	145–2649	1084	675

LVEMP data in Figs. 7, 9, and 10 (Machiwa et al., 2003, Fig. 4a,b,c).
[a] Mara and Mwanza regions of Lake Victoria.

Table 11
Average THg (μg/week) and MeHg (μg/week) potentially consumed by people in the Ilagala, Lake Victoria (Mara–Mwanza), and Rwamagasa areas based on weekly consumption of 250 g Nile perch, 500 g tilapia, and 250 g catfish

Area	Source of fish	Wet weight (g) fish consumed/ week	Geomean Hg (μg/g ww) in fish[a]	Hg (μg THg/ week)	Hg (μg MeHg/ week)[b]
Species consumed					
Ilagala–Uvinza					
Lates spp. (Nile perch)	Lake Tanganyika–Malagarasi R. delta (Ilagala market)	250	23	6	5
Oreochromis spp. (tilapia)	Lake Tanganyika–Malagarasi R. delta (Ilagala market)	500	12	6	5
Clarias spp. (catfish)	Lake Tanganyika–Malagarasi R. delta (Ilagala market)	250	16	4	3
		Total Hg per week		16	13
Lake Victoria					
Lates spp. (Nile perch)	Lake Victoria (Mara–Mwanza)	250	31	8	6
Oreochromis spp. (tilapia)	Lake Victoria (Mara–Mwanza)	500	97	49	39
Clarias spp. (catfish)	Lake Victoria (Mara–Mwanza)	250	35	9	7
		Total Hg per week		66	53
Rwamagasa (background area)					
Lates spp. (Nile perch)	Lake Victoria (Mara–Mwanza)	250	31	8	6
Oreochromis spp. (tilapia)	Lake Victoria (Rwamagasa market)	500	5	3	2
Clarias spp. (catfish)	Rwamagasa background (Munekesi and Nyamsenga)	250	110	28	22
		Total Hg per week		39	31
Rwamagasa (mining impacted area)					
Lates spp. (Nile perch)	Lake Victoria (Mara–Mwanza)	250	31	8	6
Oreochromis spp. (tilapia)	Lake Victoria (Rwamagasa market)	500	5	3	2
Clarias spp.(catfish)	Rwamagasa mining impacted (Ponds 1,2,4,5,6)	250	423	106	85
		Total Hg per week		117	94

[a] Data from Table 10.
[b] MeHg=0.8*THg.

Three distinct categories of soil ingestion may be considered: (i) inadvertent ingestion of small quantities of soils and dust; (ii) occasional deliberate consumption of soil and dust; and (iii) geophagia. It is likely that all members of an exposed population will have intakes from inadvertent ingestion, although exposure is likely to be greatest for children under seven years old. Sources of soil and dust are likely to be derived from both outdoors and indoors, and the relative magnitude of exposure will depend greatly on the habits and behaviour of an individual. Despite the wide number of studies, considerable uncertainties still exist in data relating to this activity (e.g., Simon, 1998). Estimated median inadvertent soil ingestion rates range from 25 to 81 mg soil/day for children (Davies, 1990; Calabrese, 1989) and from 0.5 to 517 mg soil/day for adults (Calabrese et al., 1990), although it should be noted that a high level of uncertainty applies to these estimates. WHO (2001) suggests 20 mg per day whereas Campbell et al. (2003a) suggested 35 mg/day for adults and 50 mg/day for children in the Lake Victoria area (derived from Smith et al., 2000). Higher inadvertent ingestion rates may be encountered in the Rwamagasa area

where people working in and close to the mineral processing centres will be exposed to a dusty environment (Böse-O'Reilly et al., 2004).

Most young children indulge in occasional deliberate ingestion of soil as an exploratory behaviour, although there is hardly any quantitative information on the amount of soil deliberately ingested during these activities. Studies in the U.S. indicated a median soil ingestion rate of from 9 to 96 mg per day (Calabrese et al., 1991). Exposure estimates for this type of soil ingestion are determined per event, as it is unrealistic to use yearly or daily consumption as a quantitative way of expressing occasional exposure. Geophagia refers to the persistent and purposeful consumption of soil and/or dust, often in relatively large quantities. It is typically associated with children and pregnant females who may be subject to nutrient deficiencies (e.g., Cooper, 1957; Barltrop, 1966; Bicknell, 1975; Morgan et al., 1988; Lacey, 1990). Geissler et al. (1998), indicated that a large proportion of male and female children in Kenya practise geophagy up to the age of 16 years, with an average soil consumption rate of 25 g per day. Geophagy has also been recorded as being prevalent in Tanzania amongst pregnant females on the coastal plains (Antelman et al., 2000) and slopes of Mount Kilimanjaro (Knusden, 2002) and its presence is therefore likely to be widely established throughout Tanzania. No information on soil eating was collected during the medical assessment in the Rwamagasa area (Böse-O'Reilly et al., 2004).

The estimated potential chemical exposure from soil and dust ingestion is summarised in Table 12. It should be noted that this calculation does not include dust inhaled and transferred to the gut and assumes that all of the ingested Hg is of a similar bioavailability to the forms of Hg administered during animal experiments from which the tolerable daily intakes have been derived. Tests to define the actual bioaccessibility of Hg in contaminated soils, such as those described in Smith et al. (2000) have yet to be validated.

Table 12
Predicted exposure from ingestion of soil/dust containing 9 mg Hg / kg

	Inadvertent[a]	Occasional deliberate[b]	Geophagia[a]
Soil ingested (g): Central estimate	0.08	0.096	26
Soil ingested (g): Worst case estimate	0.2	13.6	85
Exposure (μg Hg): Central estimate	0.72	0.86	230
Exposure (μg Hg): Worst case estimate	1.8	120	770

[a] Ingestion and exposure per day.
[b] Ingestion and exposure per event.

From the results presented in Table 12, it is clear that elevated exposures to Hg can result from the occasional deliberate and habitual consumption of contaminated soils and dusts. For example, the JECFA PTWI of 0.3 mg for Hg, which is equivalent to 26 μg/day for a 30-kg child is exceeded by an individual practising geophagia (central estimate and worst-case) or, on a case by case basis, by an individual occasionally consuming soil/dust (worst-case). The recorded practice of geophagy by pregnant females is of particular concern in this regard given the sensitivity of the foetus to Hg.

The inadvertent ingestion of dusts and soils, even those having Hg concentrations significantly above the regional background, and hence considered to be moderately contaminated, does not appear to lead to a significantly excessive exposure to Hg. For example, comparison of exposures due to inadvertent ingestion of soils and/or dusts (0.72 to 1.8 μg/day or 5 to 13 μg/week) is typically less than individual exposure via other dietary sources water, rice, and fish. This is consistent with the observations made by Campbell et al. (2003a) and is subject to similar observations on Hg bioavailability. However, given the uncertainties involved in estimating inadvertent dust and soil intake in the rural Rwamagasa environment, exposure via this route, in addition to more classical geophagic behaviour, should be considered in future studies.

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References

Antelman G, Msamanga GI, Spiegelman D, Urassa EJN, Narh R, Hunter DJ, et al. Nutritional factors and infectious disease contribute to anaemia among pregnant women with Human Immunodeficiency Virus in Tanzania. J Nutr 2000;130:1950–7.

Appleton JD. A study of the extent of mercury and related chemical pollution along the Naboc River, Monkayo, Davao del Norte; Hijo River, Apokon ore processing site; and their neighbouring areas (rice fields and banana plantations) A report for UNIDO Project DP/PHI/98/00511-02. British Geological Survey; 2000. 108 pp.

Appleton JD, Taylor H, Lister TR, Smith B, Drasch G, Boese-O'Reilly S. Final Report for an Assessment of the Environment and Health in the Rwamagasa area, Tanzania. UNIDO Project EG/GLO/01/G34. British Geological Survey Commissioned Report CR/04/129; 2004. 306 pp.

Asano S, Eto K, Kurisaki E, Gunji H, Hiraiwa K, Sato M, et al. Acute inorganic mercury vapor inhalation poisoning. Pathology International 2000;50(3):169–74.

Babut M, Sekyi R, Rambuad A, Potin-Gautier M, Tellier S, Bannerman W, et al. Improving the environmental management of small-scale gold mining in Ghana: a case study of Dumasi. J Clean Prod 2003;11:215–21.

Barltrop D. The prevalence of pica. Am J Dis Child 1966;112: 116–23.

Barth H. Explanatory notes on the 1:500,000 provisional map of the Lake Victoria goldfields, Tanzania. Geol Jahrb, Reihe B Reg Geol Ausl 1990;72:1–59.

Berzas Nevado JJ, García Bermejo LF, Rodríguez Martín-Doimeadios RC. Distribution of mercury in the aquatic environment at Almaden, Spain. Environ Pollut 2003;122(2):261–71.

Bicknell J. Pica: a childhood symptom. London: Butterworths; 1975.

Borg G. The Geita gold deposit in NW Tanzania: geology, ore petrology, geochemistry and timing of events. In: Anonymous, editor. Metallogenesis of selected gold deposits in AfricaGeologisches Jahrbuch Reihe D: Mineralogie, Petrographie, Geochemie, Lagerstaettenkunde. Stuttgart, Federal Republic of Germany: Schweizerbart in Komm.; 1994, pp. 545–95.

Böse-O'Reilly S, Drasch G, Drasch K, Maydl S. Medical investigation of 250 people living in the Rwamagasa area, Geita District, United Republic Of Tanzania. Final report, UNIDO Project EG/GLO/01/G34. Munich, Germany: Institute of Forensic Medicine, Ludwig-Maximilians University; 2004.

Calabrese EJ. How much soil do young children ingest: an epidemiological study. Regul Toxicol Pharmacol 1989;10: 113–23.

Calabrese EJ, Stanek EJ, Gilbert CE. Adult soil ingestion estimates. In: Kostecke PT, Calabrese Lewis EJ, editors. Petroleum contaminated soils 3: School of Public Health, Environmental Health Sciences Programme. Amherst, USA: Lewis; 1990, pp. 349–56.

Calabrese EJ, Stanek EJ, Gilbert CE. Evidence of soil pica behaviour and quantification of soil ingested. Human Exp Toxicol 1991;10:245–9.

Campbell LM, Dixon DG, Hecky RE. A review of mercury in Lake Victoria, East Africa: implications for human and ecosystem health. J Toxicol Environ Health, Part B Crit Rev 2003a;6(4): 325–56.

Campbell LM, Osano O, Hecky RE, Dixon DG. Mercury in fish from three rift valley lakes (Turkana, Naivasha and Baringo), Kenya, East Africa. Environ Pollut 2003b;125(2):281–6.

Coetzee L, du Preez HH, van Vuren JHJ. Metal concentrations in *Clarias gariepinus* and *Labeo umbratus* from the Olifants and Klein Olifants River, Mpumalanga, South Africa: zinc, copper, manganese, lead, chromium, nickel, aluminium and iron. Water SA 2002;28(4):433–48.

Cooper M. Pica. Springfield, Illinois, USA: Thomas; 1957.

Davies S. Quantitative estimates of soil ingestion in normal children, between the ages of 2 and 7 years: population-based estimates using aluminium, silicon and titanium as soil tracer elements. Arch Environ Health 1990;45:112–22.

Eccles DH. Field guide to the freshwater fishes of Tanzania FAO species identification sheets for fishery purposes. Rome: FAO; 1992.

Environment Agency. Soil guideline values for inorganic mercury contamination. UK: Environment Agency Bristol; 2002.

FAO/WHO. Summary and conclusions of the sixty-first meeting of the Joint FAO/WHO Expert Committee on Food Additives (JECFA), Rome, 10–19 June 2003; JECFA/61/SC; 2003.

Ferguson C, Darmendrail D, Frier K, Jensen BK, Jensen J, Kasamas H, et al. Risk assessment for contaminated sites in Europe. Nottingham, UK: LQM Press; 1998.

Geissler PW, Mwaniki DL, Thiongo F, Michaelsen KF, Friis H. Geophagy, iron status and anaemia among primary school children in Western Kenya. Trop Med Int Health 1998;3(7): 529–34.

Gladher CM, Mnali S, Muhongo S, Petro F, Rasmussen TM, Stendal H, et al. An integrated approach to mineral exploration and environmental assessment in southern and eastern Africa–a pilot study in Tanzania 2000/16. Danmarks og Grønlands Geologiske Undersøgelse; 2000.

Glahder CM, Appel PWU, Asmund G, Mercury in Soap in Tanzania. NERI Technical Report No. 306. Denmark: National Environmental Research Institute; 1999. 19 pp.

Gray JE, Meier AL, O'Leary RM, Outwater C, Theodorakos PM. Environmental geochemistry of mercury deposits in south-western Alaska: mercury contents in fish, stream-sediment, and stream-water samples. US Geol Surv Bull 1996;2152:17–29.

Gustin MS, Taylor GE, Leonard TL. High levels of mercury contamination in multiple media of the Carson River drainage basin of Nevada: implications for risk assessment. Environ Health Perspect 1994;102(9):772–8.

Haines ML, Brydges K, MacDonald MJ, Smith SL, MacDonald DD. A review of environmental quality criteria and guidelines for priority substances in the Fraser River Basin. Supporting Documentation. DOE FRAP 1994-31. Vancouver: Environment Canada; 1994.

Harada M, Nakachi S, Cheu T, Hamada H, Ono Y, Tsuda T, et al. Monitoring of mercury pollution in Tanzania: relation between head hair mercury and health. Sci Total Environ 1999;227(2–3): 249–56.

Horvat M, Nolde N, Fajon V, Jereb V, Logar M, Lojen S, et al. Total mercury, methylmercury and selenium in mercury polluted areas in the province Guizhou, China. Sci Total Environ 2003;304(1–3):231–56.

Ikingura JR, Akagi H. Monitoring of fish and human exposure to mercury due to gold mining in the Lake Victoria goldfields, Tanzania. Sci Total Environ 1996;191(1–2):59–68.

Ikingura JR, Akagi H. Proceedings of the international workshop on health and environmental effects of mercury, impacts of mercury from artisanal gold mining in Africa 2002. University of Dar es Salaam, 19–20 November 2002, pp. 56–65.

Ikingura JR, Akagi H. Total mercury and methylmercury levels in fish from hydroelectric reservoirs in Tanzania. Sci Total Environ 2003;304(1–3):355–68.

Ikingura JR, Mutakyahwa MKD, Kahatano JMJ. Mercury and mining in Africa with special reference to Tanzania. Water Air Soil Pollut 1997;97(3–4):223–32.

James TC. Thermal springs in Tanzania. Trans Inst Min Metall, B 1967;76:B1–18.

Kahatano JMJ, Mnali SR, Akagi H. Study of mercury levels in fish and humans in Mwakitolyo Mine and Mwanza Town in the Lake Victoria Goldfields, Tanzania. In: Landner L, editor. Small scale mining in African countries. Prospects, policy and environmental impacts 1997; 1997. pp. 159–70.

Kinabo C. Mercury pollution associated with artisanal mining on Lake Victoria Goldfield, in Tanzania. In: Ebinghaus R, Petersen U, von Tuempling U, editors. Fourth international conference on mercury as a global pollutant: book of abstracts. Geesthacht, Federal Republic of Germany: GKSS-Forschungszentrum; 1996. pp. 335.

Kinabo CP. Comparative analyses of mercury contents in cosmetics and soaps used in the city of Dar es Salaam. Proceedings of the International Workshop on Health and Environmental Effects of Mercury-Impacts of Mercury from Artisanal Gold Mining in Africa. National Institute for Minamata Disease, Japan and University of Dar es Salaam, Tanzania; 2002a. pp. 173–86.

Kinabo C. Comparative analyses of Hg-concentration in domestic ducks (*Anser spp.*) from Mgusu mining village in Geita, Mwanza and Dar es Salaam. Proceedings of the international workshop on health and environmental effects of mercury—impacts of mercury from artisanal gold mining in Africa. National Institute for Minamata Disease, Japan and University of Dar es Salaam, Tanzania, University of Dar es Salaam, Tanzania; 2002b. pp. 215–22.

Kinabo C, Lyimo E. Preliminary studies of mercury contamination in various food crops at Mgusu mining village in Geita, Tanzania. Proceedings of the international workshop on health and environmental effects of mercury—impacts of mercury from artisanal gold mining in Africa. National Institute for Minamata Disease, Japan and University of Dar es Salaam, Tanzania, University of Dar es Salaam, Tanzania; 2002. pp. 204–14.

Kishe MA, Machiwa JF. Distribution of heavy metals in sediments of Mwanza Gulf of Lake Victoria, Tanzania. Environ Int 2003;28(7):619–25.

Knusden JW. Akula Udongo (Earth Eating Habit): a social and cultural practice amongst Chagga women on the slopes of Mount Kilimanjaro. Afr J Indig Knowl Syst 2002;1.

Lacey EP. Broadening the perspective of pica: literature review. Public Health Rep 1990;105:29–35.

Machiwa JF, Kishe MA, Mbilinyi HG, Mdamo A, Mnyanza O. Impact of gold mining in Lake Victoria Basin on mercury levels in the environment. Lake Victoria Environmental Management Project Report; 2003. 46 pp.

Morgan H, Smart GA, Sherlock JC. Intakes of metals. Sci Total Environ 1988;75:71–100.

Mutakyahwa MKD. Mercury contamination due to gold mining in Tanzania. Proceedings of the international workshop on health and environmental effects of mercury—impacts of mercury from artisanal gold mining in Africa. National Institute for Minamata Disease, Japan and University of Dar es Salaam, Tanzania; 2000. pp. 21–9.

Nakagawa R, Yumita Y. Change and behaviour of residual mercury in paddy soils and rice of Japan. Chemosphere 1998;37:1483–7.

RIVM. Technical Evaluation of Intervention Values for Soil/ Sediment and Groundwater. RIVM Report 711701023. Bilthoven, The Netherlands, National Institute of Public Health and the Environment 2001.

Semu E, Guttormsen D, Bakken L. Microbial-populations and activity in 2 soils of Tanzania as influenced by mercury. MIRCEN J Appl Microbiol Biotechnol 1989;5(4):533–42.

Simon SL. Soil ingestion by humans: a review of history, data, and aetiology with application to risk assessment of radioactively contaminated soil. Health Phys 1998;74(6):647–72.

Sindayigaya E, Van Cauwenbergh R, Robberecht H, Deelstra H. Copper, zinc, manganese, iron, lead, cadmium, mercury and arsenic in fish from Lake Tanganyika, Burundi. Sci Total Environ 1994;144(1–3):103–15.

Smith B, Rawlins BG, Cordeiro MJAR, Hutchins MG, Tiberindwa JV , Sserunjogi L, et al. The bioaccessibility of essential and potentially toxic trace elements in tropical soils from Mukono District, Uganda. J Geol Soc 2000;157:885–91.

Tiercelin JJ, Pflumio C, Castrec M, Boulegue J, Gente P, Rolet J, et al. Hydrothermal vents in Lake Tanganyika, East African rift system. Geology 1993;21:499–502.

University of Dar es Salaam. Monitoring of mercury and other heavy metal pollution in gold mining areas around lake Victoria, Tanzania Final report. Dar es Salaam: Department of Geology, University of Dar es Salaam; 1994. 55 pp.

USEPA, 1996. Soil Screening Guidance: Technical Background Document. EPA/540/R95/128.

van Straaten P. Gold mineralization in Tanzania: a review. In: Foster RP, editor. Gold '82; the geology, geochemistry and genesis of gold deposits. Rotterdam, Netherlands: A.A. Balkema; 1983, pp. 673–85.

van Straaten P. Human exposure to mercury due to small scale gold mining in northern Tanzania. Sci Total Environ 2000a; 259(1–3):45–53.

van Straaten P. Mercury contamination associated with small-scale gold mining in Tanzania and Zimbabwe. Sci Total Environ 2000b;259(1–3):105–13.

Veiga MM, Baker R. Protocols for environmental and health assessment of mercury released by Artisanal and Small-Scale Gold Miners (ASM). Vienna: UNIDO; 2003.

Wagner S. Socio-economic survey of Rwamagasa mining site in Geita district, report of sociologist/national expert WID to UNID; July 2003.

WHO. Environmental health criteria 86: mercury-environmental aspects. Geneva: World Health Organisation; 1989.

WHO. Depleted uranium: sources, exposure and health effects. WHO/SDE/PHE/01.1. Geneva: World Health Organisation; 2001.

Williams TM, Rawlins BG, Smith B, Breward N. In-vitro determination of arsenic bioavailability in contaminated soil and mineral beneficiation waste from Ron Phibun, southern Thailand: a basis for improved human risk assessment. Environ Geochem Health 1998;20(4):169–77.